Magnetically stabilized AB interface in rotating superfluid ^{3}He

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Abstract

Vortex lines in the A and B phases of superfluid ^{3}He have different structure and quantization. How do they then interact at the AB phase boundary? We discuss an experimental setup where the AB interface is stabilized in a long cylindrical container with a magnetic barrier field. It divides the sample in A and B-phase sections which are maintained in a homogeneous low-field NMR environment over the temperature interval where the supercooled A phase exists in the smooth-walled quartz tube. With two independent NMR spectrometers the vortex lines in the two phases can then be studied as a function of the rotation velocity of the cryostat. Simultaneously, by adjusting the barrier field and temperature, the sample can be changed from single phase to two-phase configurations with one or two AB interfaces. Using this setup the first example of a shear-flow instability in superfluids was discovered [1].

Key words: superfluidity; ^{3}He; AB interface; NMR measurement; superconducting magnets; quantized vortex lines

The design of the experimental setup is shown in Fig. 1. The central part is a long quartz cylinder ($\varnothing 6 \times 110$ mm) which contains the ^{3}He sample. On the bottom it is sealed off with a $\varnothing\, 0.7$ mm orifice to prevent vortices from leaking into the container from the heat exchanger volume on the nuclear cooling stage of the rotating cryostat. The connection to the heat exchanger is through a tubular extension ($\varnothing 6 \times 45$ mm) of the quartz cylinder. End compensated superconducting solenoids surround the sample volume, producing the barrier field in the middle and the homogeneous NMR fields on the top for the A-phase measurement and on the bottom for the B phase. The magnetic field design is carefully executed to maintain field homogeneity in the NMR regions also while the current in the barrier solenoid is swept over its entire range. This requirement is the cause for the long sample volume, even though additional counterwound bucking sections have been added on all three solenoids to improve the longitudinal containment of their fields.

Owing to the poor thermal conductivity and large specific heat of the long ^{3}He sample above 50 mK, it takes more than a week to cool down from the filling and pressurizing temperature of 1 K. The precooling from 50 to 18 mK is fast, requiring less than two days. At this point the barrier field is swept up. When the demagnetization of the nuclear cooling stage is started, T_c is reached in about 8 hours. The transition through T_c is normally performed at a slow rate of $(20 \ldots 100)$ nK/s while the cryostat is rotating. This procedure has been found to yield the most homogeneous order-parameter textures, when the whole sample has finally been cooled to the A phase. During further cooling the B phase appears first at the coldest place with the roughest surface [2], which here is the heat exchanger volume on the nuclear cooling stage. It then starts to ascend in the sample cylinder, but stops at a height z, where the barrier field equals the field of the thermodynamic AB transition at temperature T and pressure p: $H_b(z) = H_{AB}(T, p)$ [3]. On further cooling the supercooled A phase remains above the AB interface in the upper section of the sample, until at a certain temperature (dependent on pressure, prehis-

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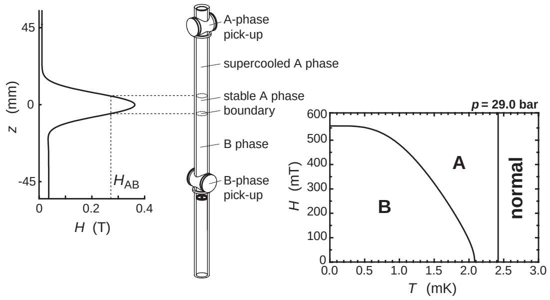

Fig. 1. *(Left)* Location of the AB phase boundary in the sample cylinder ($p = 29.0$ bar, $T = 1.6$ mK$= 0.65\,T_c$, $I_b = 4.0$ A). *(Right)* Phase diagram at 29.0 bar, where the first order AB transition line is measured by Hahn *et al.* [3].

tory, and container walls) it abruptly and irreversibly turns into B phase.

At low magnetic field the A phase supercools lower the smoother the container walls are on the scale of the superfluid coherence length $\xi(T, p) \sim 10 \ldots 100$ nm. In general, the quality of the container walls can be evaluated on the basis of two measurements: (i) how far the A phase supercools and (ii) how high the critical velocity for vortex-line formation can be pushed in the B phase. To assure smooth surfaces, all corners and edges of the quartz container are flamed. Before final assembly the inside surfaces are carefully etched (5% hydrofluoric - 30% nitric acid) and washed, to remove any left-over rough spots. The A phase above the AB interface supercooled to $0.57\,T_c$ at 29.0 bar pressure and to $0.50\,T_c$ at 33.7 bar. These are usual values for a fused quartz surface. The B-phase critical rotation velocity for nucleating vortices on the outer cylinder wall is not known, because vortices start leaking into the sample volume through the bottom orifice already at 2.2 rad/s [4].

The magnet system consists of three concentric cylindrical parts: the innermost barrier solenoid, the two NMR magnets in the center, and the superconducting shield as the outer cover. The Nb shield improves field homogeneity and provides immunity from external fields. To help contain the barrier field and to prevent shielding currents from driving the Nb shield normal, the barrier coil is wound on a smaller diameter. Some specifications of the system are listed in Table 1.

All coil formers are machined from brass. To boost the Q values of the NMR tank circuits, RF losses in the coil formers is avoided by coating the brass bores with high-conductivity shielding, an oxygen-annealed copper cylinder [5]. The magnet system is suspended from the bottom of the mixing chamber. Thus the heating produced while sweeping the coils is not released to the nuclear stage. To prevent quenches and to minimize requirements on the current supplies, the solenoids are designed to operate at low currents. All coils are wound with a ⌀ 0.12 mm multifilamentary superconducting

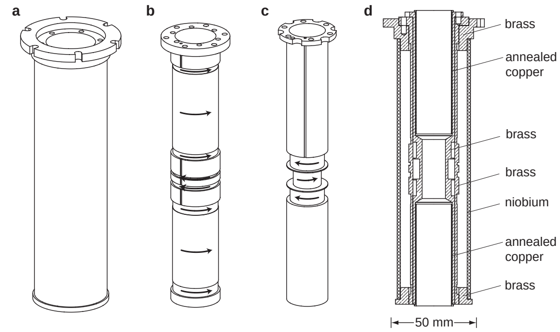

Fig. 2. Design of the superconducting system of solenoids. The arrows denote the winding direction. (a) Superconducting shield. (b) The two coil formers of the NMR magnets. (c) Coil former of the barrier magnet. (d) Coaxial assembly of the parts which slide inside each other.

wire of NbTi in a CuNi matrix. The dimensions and windings of the magnet system were optimized to reduce sensitivity with respect to contraction on cooling to 4 K, and to machining and winding errors.

Both NMR pick-up coils consist of 2×26 turns wound in two layers into two slots on a quartz coil former with ⌀ 50 μm multifilamentary CuNi coated superconducting wire. They are part of high Q LC tank circuits, $Q_A = 9300$ at 332 kHz and $Q_B = 4800$ at 1.15 MHz. The tuning capacitors are high-quality ceramic chips, 9 nF in total for A-phase and 0.8 nF for B-phase resonance. The capacitors are thermally anchored to the nuclear cooling stage, to enhance their Q value and stability during the measurement. In each case the output from the tank circuit is connected via a shielded superconducting cable to a cryogenic GaAs MESFET amplifier which operates in a 4 K environment inside the vacuum jacket of the cryostat.

The present technique of stabilizing the AB boundary, similar to that in Ref. [6], is easy to use because during cooling the AB interface stabilizes automatically in the middle of the sample. The AB interface turned out to remain stable when the cryostat is set in rotation, even when the lower B-phase section remains in metastable vortex-free state up to high rotation velocity. Also the regular AB sequence of phases in the sample volume can be easily converted in the temperature range of A-phase supercooling to single-phase A or B, which is important for reference measurements without an AB interface. One more interesting configuration is BAB at high barrier fields, to investigate

Table 1
Superconducting coil system. The homogeneity is the FWHH of the normal phase NMR absorption signal.

coil	clear bore (mm)	H (mT)	I (A)	homogeneity
A	25	10	1.0	$3 \cdot 10^{-4}$
B	25	35	1.8	$7 \cdot 10^{-4}$
Barrier	14	< 500	< 8.0	–

the influence of two simultaneous AB interfaces. By sweeping the current in the barrier magnet to low values the shape of the AB interface can be varied. When the field is ramped down sufficiently, eventually the A phase volume is reduced to a ring around the outer container wall in the center of the barrier magnet [7]. If the field is then swept back up, the toroidally shaped A phase volume is (almost reversibly) changed back into a singly connected layer in the BAB configuration.

The present sample container is the longest in which vortex lines so far have been studied in rotating ^{3}He superfluids. The long length, having two spectrometers and the ability to apply different field profiles over the sample offer extra possibilities over the earlier much shorter samples with one spectrometer in a uniform field. It becomes possible to measure the flight time in different vortex formation processes when the small initially formed vortices expand to rectilinear vortex lines. Such measurements yield the mutual-friction damping. Another interesting possibility is to study the stability of different vortex structures in the A phase when the magnetic field in one half of the sample is swept to zero.

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